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The long range goal of this project is the creation of nanostructures using light fields to manipulate atoms. To illustrate some of the theoretical progress we have made along these lines, we summarize our results on (i) a *conical lens* that can be used to focus atoms to a single spot, (ii) a *multi-color field geometry* that can be used to produce high-harmonic, sinusoidal, spatial matter gratings in a single atom-field interaction zone, (iii) a *filtered Talbot lens* that combines atom focusing and the Talbot effect (self imaging of periodic gratings) to produce high spatial period, high resolution matter gratings, (iv) atom focusing in the Raman-Nath regime and (v) nonlinear ground state pump-probe spectroscopy. Experimental achievements include (i) creation and detection of ground state *coherence* gratings, (ii) creation and detection of high order atomic density gratings using *echo* techniques, (iii) the use of an *optical mask* for the production and measurement of periodic density gratings, (iv) the production of a bright atomic beam source, (v) the creation of magnetic coherence gratings in the atomic Rb beam, and (vi) transverse cooling of the atomic Rb beam.

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## I. LIST OF ILLUSTRATIONS

## II. STATEMENT OF THE PROBLEM STUDIED

The long-term goal of this project is to create nanostructures by passing a beam of atoms through two or more standing wave light fields. Following interaction with the standing wave fields, the atomic density contains all even spatial harmonics of the standing wave light field. At appropriate distances following the interaction with the light fields the different harmonics are focused, enabling one to isolate each of the harmonics. By transferring the atomic density spatial distribution to a surface, one can create pure harmonic gratings having periods as small as tens of nanometers. In addition to forming pure harmonic gratings, we are working on methods to effectively focus atoms with high resolution (spot size of order 15 nm) and high periodicity (of order 50 nm). Methods for probing the density patterns with nanometer resolution are being explored.

## III. SUMMARY OF THE MOST IMPORTANT RESULTS

Many of the details of our accomplishments are contained in the publications listed below, as well as in the annual progress reports submitted in connection with this Grant. In this final report, we highlight some of the important results that have emerged from our investigations. The research effort is a combined theoretical-experimental program, with the theory component housed at the University of Michigan and the experimental component at New York University.

### A. Theory

Our theoretical efforts have focused on new schemes to focus atoms and to produce periodic sinusoidal matter gratings. Optical fields having wavelength $\lambda$ are used to create matter gratings having period $\lambda/2n$, where $n$ is an integer, and to focus atoms to spot sizes as small as 10 nm. To illustrate some of the theoretical progress we have made along these lines, we summarize our results on (i) a *conical lens* that can be used to focus atoms to a single spot, (ii) a *multi-color field geometry* that can be used to produce high-harmonic, sinusoidal, spatial matter gratings in a single atom-field interaction zone, (iii) a *filtered Talbot lens* that combines atom focusing and the Talbot effect to produce high spatial period, high resolution matter gratings, (iv) atom focusing in the Raman-Nath regime and (v) nonlinear ground state pump-probe spectroscopy.

#### 1. *Conical lens for atom focusing*

Following the first observations of atom focusing by a standing wave field, a number of different techniques to focus atoms have been proposed and realized using atom-resonant light field interactions. In most experiments an atomic beam is focused by a resonant standing wave optical field. This field produces a lens array for atoms located near the standing wave field's antinodes. At the focal plane the atomic spatial distribution consists of a periodic set of lines or dots having extremely small widths and distanced from one another by $\lambda/2$, where $\lambda$ is the wave length of the standing wave field. In spite of the extremely high spatial resolution (10-20 nm) achieved to date, the application of this technology to atomic lithography is restricted since a set of lines cannot be used to draw a pattern of arbitrary shape on a substrate. To achieve this goal one requires a field intensity spatial distribution that has a single sharp extremum to serve as a single lens for atoms. Using a technique similar to that proposed by Ashkin twenty-five years ago to trap neutral atoms, one can build this lens. By cutting an annulus in an opaque screen of mean radius $a$ and thickness $h << a$, centered at $x = 0$ and $y = 0$, one can carve a laser beam propagating along the $z$-axis into a cylindrical shell (see Fig. 1). When reflected from a conical mirror, this beam becomes a cylindrical wave converging towards the $z$-axis. Since the field after reflection can be treated as a continuous set of traveling waves all converging to the $z$-axis, one expects that the intensity profile in the plane $(x, y)$ contains only one sharp extremum and, therefore, acts as a lens for an atomic beam propagating along the $z$-axis. The focused atoms can be deposited on a substrate, producing a spot. The entire apparatus can be translated to produce lines of atoms of arbitrary length and shape with line widths of order of the focus spot size (10-20 nm or even narrower). One can estimate that the efficiency of focusing for such a lens is $10^2$-$10^3$ better than that achieved with standing wave fields.

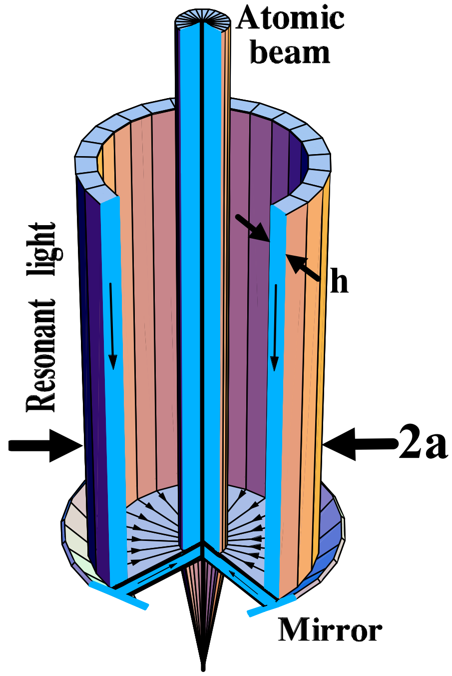


FIG. 1. Schematic diagram of a conical lens. Light propagating along a cylindrical shell reflects from a conical mirror and forms a lens that focuses an atomic beam onto one spot.

Increasing the focusing efficiency is extremely important for atom lithography. For example, 300 mW laser sources have been used to focus Cr atoms into a set of lines having width 10 nm. Estimates show that using the scheme described above one can focus Cr atoms to a single spot having the same radius (10 nm) with a laser power of 20 $\mu$W only. Using low to moderate laser power, one can construct a conical lens that should improve the current resolution limits in atom nanolithography. We have carried out calculations for the conical lens using both numerical and analytical techniques [1] (reference numbers correspond to references in the Bibliography section) in the thin lens regime, when the Raman-Nath approximation is valid. We have derived an integral representation for the atomic wave function after scattering from the field. Numerical evaluation of this integral allows us to determine the position of the focal plane, and the shape and width of the atomic spatial distribution at this plane.

### *2. Multicolor field geometry*

Consider the field configuration shown in Fig. 2, when $\delta_1 = -\delta_2 = \delta$. In the atomic rest frame, the fields shown constitute a pulse of radiation having duration $T$, and it is assumed that $|\delta|T > 1$. In order to create an atomic density which varies as $\cos(2kz)$, where $k$ is the field propagation constant, one must have a two-photon transition in which one photon is absorbed from the field having frequency $\Omega$ and emitted into either the field having frequency $\Omega+\delta$ or the field having frequency $\Omega - \delta$. However, this two-photon process is not resonant and will average to zero over the pulse duration. In other words, the second spatial harmonic that is produced in such two-photon processes is totally suppressed. However, a four photon process involving the absorption of two photons of frequency $\Omega$ and emission of photons at frequencies $\Omega + \delta$ and $\Omega - \delta$ is resonant and leads to an atomic density that varies as $\cos(4kz)$. Thus, with a single field interaction zone using a standing wave field having wavelength $\lambda$, it is possible to produce atom gratings having period $\lambda/4$. More generally, if the frequencies of the waves shown in Fig. 2 are $\Omega$, $\Omega + \delta_1$, and $\Omega + \delta_2$, and if one chooses the pulse duration $T$ to be much larger than $|\delta_j|^{-1}$ and takes $n_1\delta_1 + n_2\delta_2 = 0$, where $n_1$ and $n_2$ are integers with no common factors, one can create matter gratings having period $\lambda/[2(n_1 + n_2)]$. A proper choice of the field intensities allows one to form atomic density patterns that are very nearly sinusoidal.

Depending on the frequency $\Omega$, either atom amplitude or phase gratings can be produced. For resonant fields, amplitude gratings are carved in individual state populations. For $|\Omega-\omega|T > 1$ ($\omega$ is the atomic transition frequency), a phase grating is produced in the ground state probability amplitude that leads eventually to a focused series of lines or dots separated by $\lambda/[2(n_1 + n_2)]$. Shown in Figs. 3 and 4 are atom amplitude and phase gratings having periods $\lambda/10$ and $\lambda/6$, respectively. The $\chi_j$'s are the Rabi frequencies of the laser fields. A course graining of the relevant mathematical equations enables one to obtain analytical expressions for the atomic density over a wide range of field amplitudes and detunings [2]. This technique can be extended to the echo experiment and to experiments where photon recoil plays a critical role. In this way, the lowest harmonic appearing in the atomic density can be suitable for some nanolithographic applications.

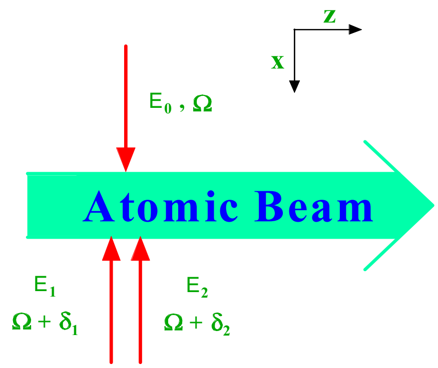


FIG. 2. Atom-field geometry. All fields overlap in the interaction region. The detunings $\delta_1$ and $\delta_2$ are chosen such that $|\delta_1|T, |\delta_2|T \gg 1$, where $T$ is the interaction time in the atomic rest frame.

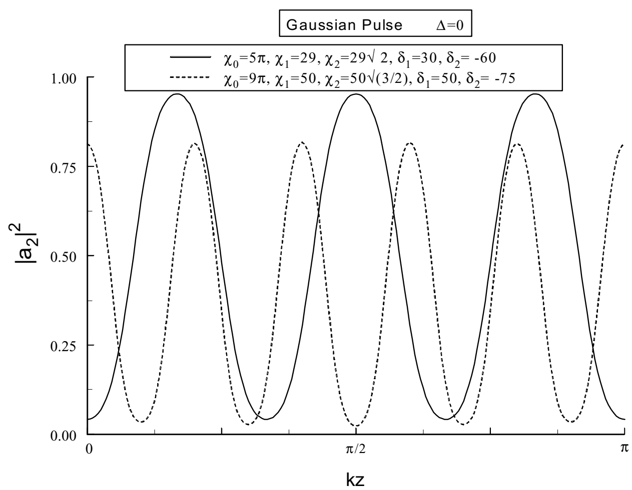


FIG. 3. Graphs of the upper state probability as a function of $kz$ for excitation by a Gaussian pulse, with $n_1\delta_1 + n_2\delta_2 = 0$. Graphs are shown for ($n_1 = 2$, $n_2 = 1$) (sixth harmonic) and ($n_1 = 3$, $n_2 = 2$) (tenth harmonic).

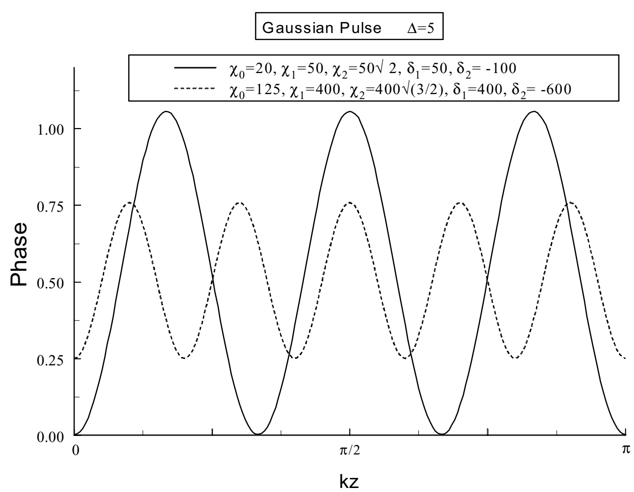


FIG. 4. Graphs of the ground state phase as a function of $kz$ for excitation by a Gaussian pulse, with $n_1\delta_1 + n_2\delta_2 = 0$. Graphs are shown for ($n_1 = 2$, $n_2 = 1$) (sixth harmonic) and ($n_1 = 3$, $n_2 = 2$) (tenth harmonic).

The multicolor field technique allows one to produce high-order harmonic gratings having period $\lambda/2n$, using resonant radiation having period $\lambda$. The grating profiles are approximately sinusoidal and can effectively diffract x-ray radiation. On the other hand, alternative methods are needed for achieving the highest resolution in atom lithography. Atom focusing offers unique possibilities in this area. Using standing wave optical fields having wavelength $\lambda$, one has been able to write a periodic array of lines or dots having period $\lambda/2$. The atomic "lines" or "dots" themselves have widths $w$ that are very small compared with $\lambda/2$; widths (half width at half maximum), as small as 6.5 nm have been achieved However, such focusing techniques result in periodic structures whose period cannot be less than $\lambda/4$.

To address this issue we developed a method which allows one to focus atoms in a periodic array of lines having the same resolution $w$ but $n$-times smaller period [3]. To obtain a $\frac{\lambda}{2n}-$period atom grating one can use the fractional Talbot effect. The atomic Talbot effect is a self-imaging of the atom density, modulated initially with a period $\lambda/2$, on the Talbot distance $L_T = \lambda^2/2\lambda_{dB}$, where $\lambda_{dB} = h/Mu$ is the atomic de Broglie wavelength, and $M$ and $u$ are the atomic mass and velocity, respectively. The fractional Talbot effect refers to the formation of $\frac{\lambda}{2n}-$period gratings at fractional Talbot distances $L_T/m$ ($m = n$ or $2n$). These gratings have the same profile as the initial $\frac{\lambda}{2}-$period grating but $n-$times smaller amplitude. The necessary condition for this effect is that the initial grating consists only of the sharp peaks having width w$\ll \lambda/2n$. Even though the fractional Talbot effect does not allow one to improve the resolution $w$, *it allows one to transform a given high resolution grating having period $\lambda/2$ into high-order gratings having the same resolution.*

An off resonant standing wave field can focus atoms at a focal distance $z_f$. One might expect that, as a result of the fractional Talbot effect, reduced period gratings should occur at distances $z_f + L_T/m$. Some numerical evidences for this effect have been obtained previously, but a more detailed analysis reveals that *the background density between the focused atoms seriously degrades the fractional Talbot effect.* Estimates and numerical calculations (see Figs. 5, 6) show that this is a strong effect. For example a ratio of background to peak density of 0.01 at $z = z_f$ can result, at the fractional Talbot distance, in changes to the atomic density that can deviate by as much as 20% from the density that would have been produced in the absence of any background density.

To overcome this difficulty we apply one more optical element, an optical mask, at the focal plane of the first standing wave field. A resonant, standing wave optical field can be used for the optical mask, filtering all atoms except those passing near the nodes of the field. The optical mask removes the background density in the focal plane. One can expect this *filtered Talbot lens* to produce perfectly periodic high-contrast, high-resolution high-order gratings. Examples of such gratings, obtained for weak and strong masking fields are shown in Figs. 5 and 6

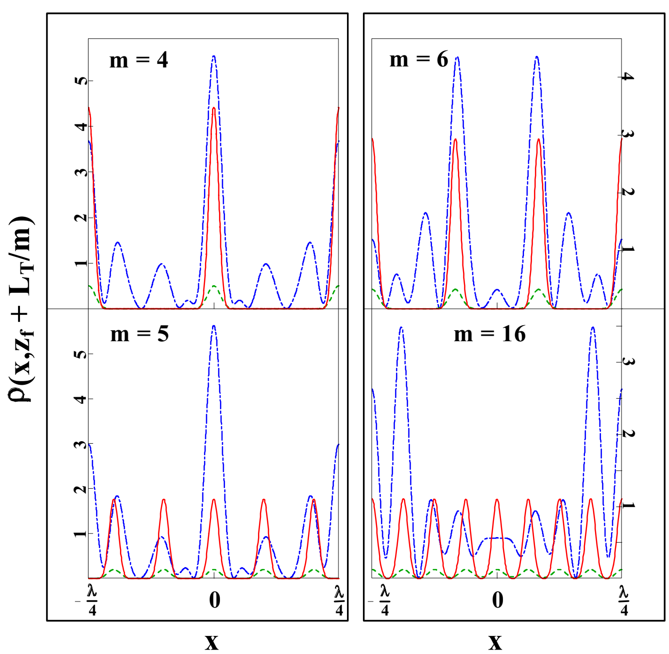


FIG. 5. Filtered Talbot lens production of high-order atomic density patterns (solid lines) at distances $z_f + L_T/m$ in the weak mask limit. For comparison, we show the spatial distributions of the metastable atomic density produced by the optical mask alone at the fractional Talbot distances (dashed lines) and by the focusing field alone at the fractional Talbot distances from the focal plane (dot-dashed lines).

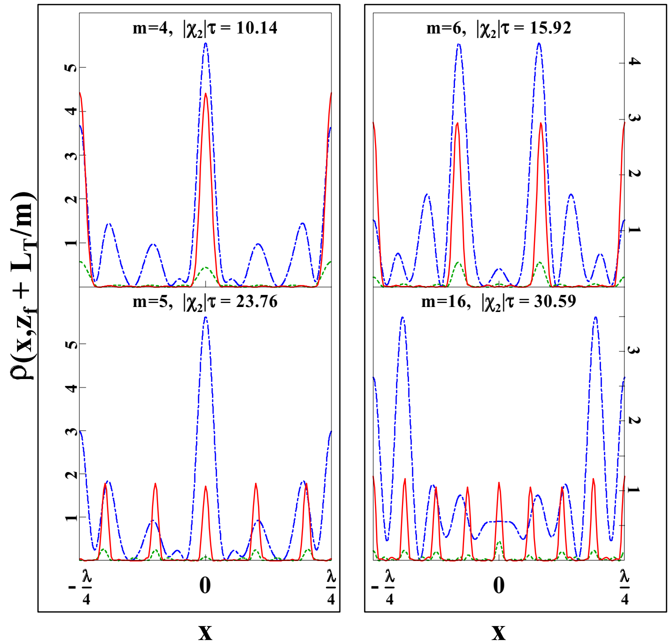


FIG. 6. The same type of density plots as those shown in Fig. 5, but for a moderate value of the interaction time $\tau$ in the strong mask limit. The parameter $|\chi_2\tau|$ ( $\chi_2$ is the Rabi frequency of the masking field) is chosen for each plot by requiring that the ratio of the maximum and minimum amplitudes of the peaks in the fractional density pattern are as close as possible to unity. In each case this choice produces the best $n$th-order fractional self-image. The mask only curves are multiplied by a factor 2.5 to enhance their visibility.

*4. Focusing of atoms by off-resonant and resonant fields.*

A detailed calculation of focusing of atoms by resonant and off-resonant standing wave, optical fields was carried out in [4]. Both Fourier analysis and scalar Kirchhoff diffraction theory were used to obtain exact numerical and analytical approximations for the spot size, focal position, atomic density at the focus, and depth of focus. These quantities are plotted in Figs. 7 and 8 for both resonant and off resonant fields as a function of laser power.

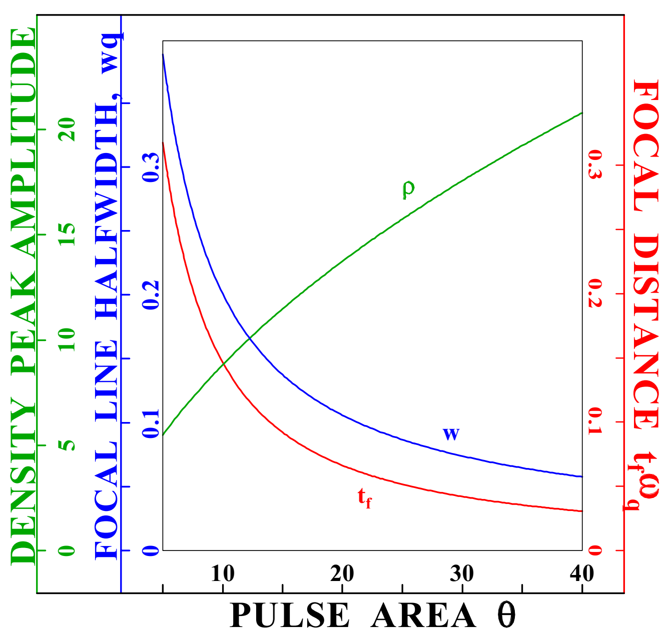


FIG. 7. Pulse area dependence of the lens parameters in far-detuned focusing: peak focal densities (curve $\rho$), spot sizes (half-widths of the density profiles at the focal planes (curve $w$) and focal distances (curves $t_f$).

The spot size $w$ is in units of $\lambda/4\pi$, and the focal plane position is in units of the Talbot length. It is seen that the parameters oscillate as a function of field strength for resonant excitation. This new structure can be explained as an interference effect. The interference is between a component of the atomic wave function that is responsible for focusing and a component that gives rise to a background signal.

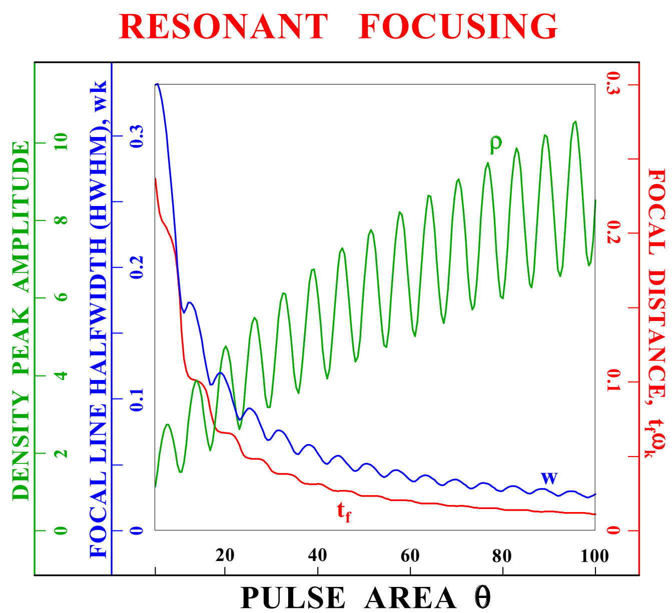


FIG. 8. The same for focusing by a resonant standing wave field.

We have shown that focusing by off-resonant fields in the Raman Nath approximation yields results that should be competitive with those obtained in the "thick lens" limit.

*5. Nonlinear, ground state spectroscopy*

In conventional pump-probe spectroscopy of an atomic vapor, one monitors the absorption of a probe field on an atomic transition that is driven simultaneously by a pump field of arbitrary strength. A calculation of the probe field absorption is relatively straightforward in the weak probe field limit. The width of these spectral components is on the order the excited state decay rates, neglecting any Doppler broadening. Experimental studies of pump-probe spectroscopy on a single transition have been few and far between.

We have proposed a method for carrying out pump-probe spectroscopy on a ground-state Raman transition in a thermal vapor [5]. The atom field geometry is indicated schematically in Fig. 9.

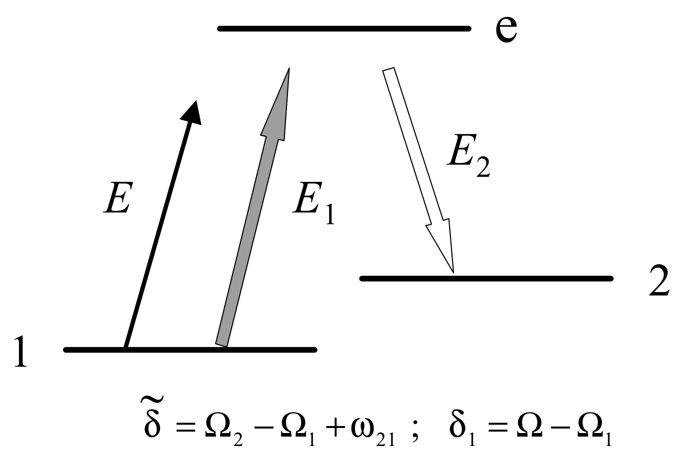


FIG. 9. Schematic diagram of the atom-field system. Fields $E_1$ and $E$ drive only the $1-e$ transition and field $E_2$ only the $2-e$ transition

Three-level atoms interact with two optical fields, $E_1$ and $E_2$, producing strong coupling between initial and final levels 1 and 2 via an intermediate excited state level $e$. Field $E_1$ couples only levels 1 and e, while field $E_2$ couples only levels 2 and $e$. In addition, there is a weak probe field $E$ that couples only levels 1 and $e$. As a consequence, fields $E$ and $E_2$ can also drive two-photon transitions between levels 1 and 2. The incident fields are assumed to be nearly copropagating so that all two-photon Doppler shifts can be neglected. In this limit and in the limit of large detuning on each single photon transition, one can consider the atoms to be stationary with regards to their interaction with the external fields. In calculating the probe absorption spectrum, one finds that all the line widths are determined by the effective ground state decay rate.

We expect this technique to be an important addition to nonlinear probes of atomic systems. It is capable of resolving recoil-induced effects in cold atomic samples or Bose condensates. One has control over setting of the recoil splittings by a choice of field directions. Moreover there is an additional control knob in this technique, the ratio of the two pump filed amplitudes, that is not available in conventional pump-probe spectroscopy.

### B. Experiment

Experimental efforts have concentrated on developing techniques for creating and detecting periodic atomic density gratings with sub-optical wavelength periods. Experiments have been carried out with Rb atoms in both a magneto-optical trap (MOT) and in an atomic beam. Much of the efforts involving the atomic beam have been toward assembling the apparatus and developing a bright source of atoms. To illustrate some of the experimental progress, we summarize our results on (i) creation and detection of ground state *coherence* gratings, (ii) creation and detection of high order atomic density gratings using *echo* techniques, (iii) the use of an *optical mask* for the production and measurement of periodic density gratings, (iv) the production of a bright atomic beam source, (v) the creation of magnetic coherence gratings in the atomic beam, and (vi) transverse cooling of the atomic beam.

#### *1. Creation and detection of ground-state coherence gratings in laser-cooled atoms and in a room-temperature vapor*

We have developed techniques to create and detect atomic ground state *coherence* gratings. Such gratings are produced by the application of one or more pulses, each consisting of two traveling-wave laser fields of orthogonal polarizations. These gratings have a period determined by the difference in wavevectors of the two traveling-wave fields. For counterpropagating fields, the period is half an optical wavelength. The gratings can be viewed by observing the light scattered by the atoms of an incoming traveling wave (see Fig. 10).

If a single standing-wave pulse is applied, the resulting grating can be viewed immediately after this pulse, and is referred to as a *magnetic grating free induction decay* (MGFID). The signal decays due to Doppler dephasing arising from the atomic motion. The time scale of the decay is determined by the angle between the two excitation beams and the transverse velocity spread. The time dependence of the decay can be used to measure the transverse velocity distribution of the atoms with high resolution. If a second pulse is applied at time $T$, the coherence grating will reform at time $2T$ due to the cancellation of the Doppler phase. The resulting signal is called a *magnetic grating echo* (MGE). Since the observed coherence is in the atomic ground state, the lifetime of the echo should be limited only by how long the atoms remain in the interaction region. In a sample of laser-cooled atoms, we have observed the effect of atomic recoil from the absorption and emission of photons [6]. The MGE was also observed in a room temperature vapor [7], and the effect of collisions with a background vapor (Ar) was observed by the effect on the MGE lifetime [8]. Increasing the pressure of the background vapor at first reduces the MGE lifetime, but for sufficiently high pressure, the MGFID lifetime *increases* due to collisional localization of the atoms.

#### *2. Creation and detection of high order atomic density gratings using echo techniques*

We have demonstrated a technique for generation and real-time detection of nano-structures in a cold Rb cloud. These structures, which are periodic gratings of atomic density, appear as a result of interference of atoms diffracted by pulses of an optical standing wave of wavelength $\lambda$ [see Figure 11(a)]. We have detected structures of period $\lambda/2$ and $\lambda/4$. Calculations indicate that these density gratings have period $\lambda/2n$ for integer $n$. While the structures with the period $\lambda/2$ are easily detected by Bragg-scattering of an optical probe beam.[Figure 11 (b)], the shorter-period structures are not. Atomic gratings of various periodicities can be produced by a pair of standing wave pulses separated by time $T_2$. Pulses with different periodicities appear at different times after the second pulse, as shown in Figure 12.

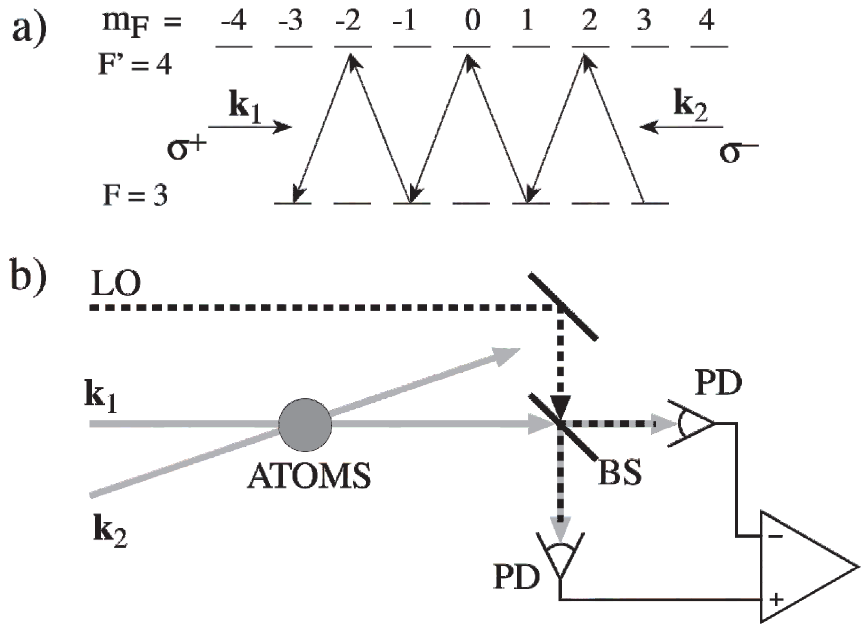


FIG. 10. (a) Level diagram of the Rb transition used in the experiments. (b) Diagram of the experimental configuration: LO, optical local oscillator; M, mirror; BS, beam splitter; PD, photodiode; **k**1 and **k**2 label the excitation beams and readout pulse (**k**2 ).

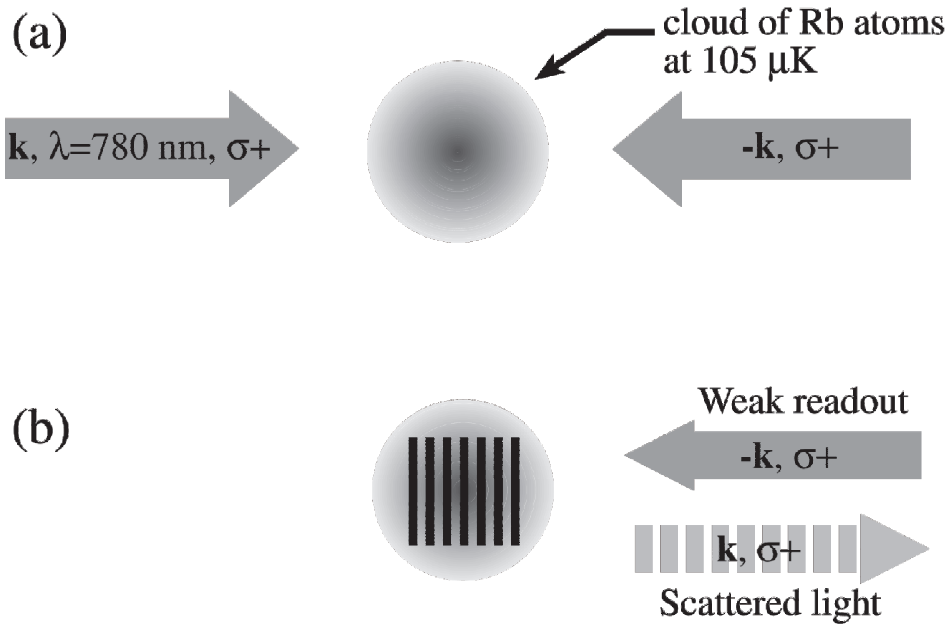


FIG. 11. Sketch of experiment to produce sub-optical-wavelength atomic gratings: (a) Cloud of cold Rb atoms is illuminated by short pulses of a standing wave made of two counter-propagating waves of the same polarization; (b) To detect $\lambda/2$ grating in the cloud, we switch on a weak field in the mode $\mathbf{k_2}$, which is coherently scattered into the mode $\mathbf{k_1}$ by the density grating.

To measure these "high-order" gratings, we apply a third standing wave pulse, which converts the atomic coherence that results in these high-order gratings into a grating with period $\lambda/2$. Figures 13 (a) and (b) show the conversion of a grating of period $\lambda/4$ into a $\lambda/2$ grating at a later time (shown by the open circles in Fig. 13). A third kind of echo with Doppler phase diagram shown in Fig. 13 (c) also appears. These three types of echo can be distinguished by when they appear as a function of times $T_2$ and $T_3$ [this time dependence is the origin of the names "slow echo" and "fast echo" in Fig. 13 (a) and (b)].

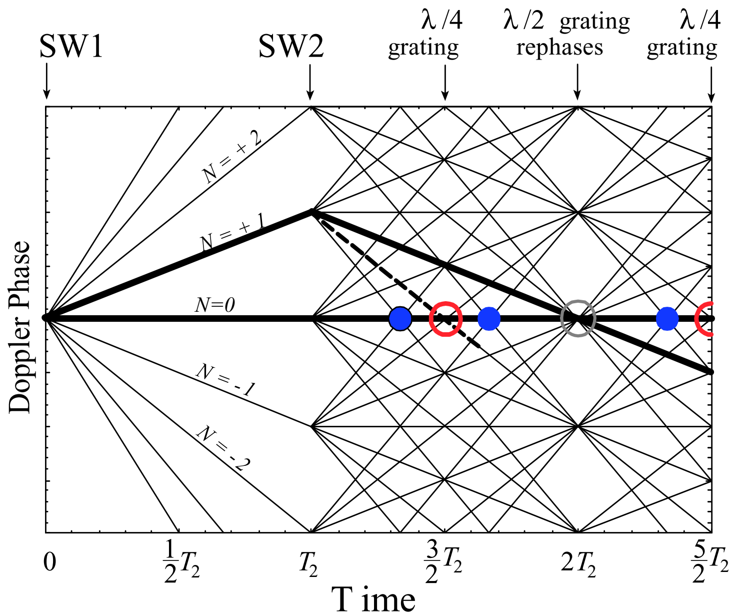


FIG. 12. Doppler phase diagram: All possible trajectories of an atom subject to two standing wave pulses, SW1 and SW2 (which are assumed to be short, and whose duration is not resolved in the plot). The wavepacket shown by the dashed trajectory produces $\lambda/4$ structure at $t = \frac{3}{2}T_2$. Solid dots at $t = \frac{4}{3}T_2$, $t = \frac{5}{3}T_2$, and $t = \frac{7}{3}T_2$ show the instants when gratings of period $\lambda/6$ form.

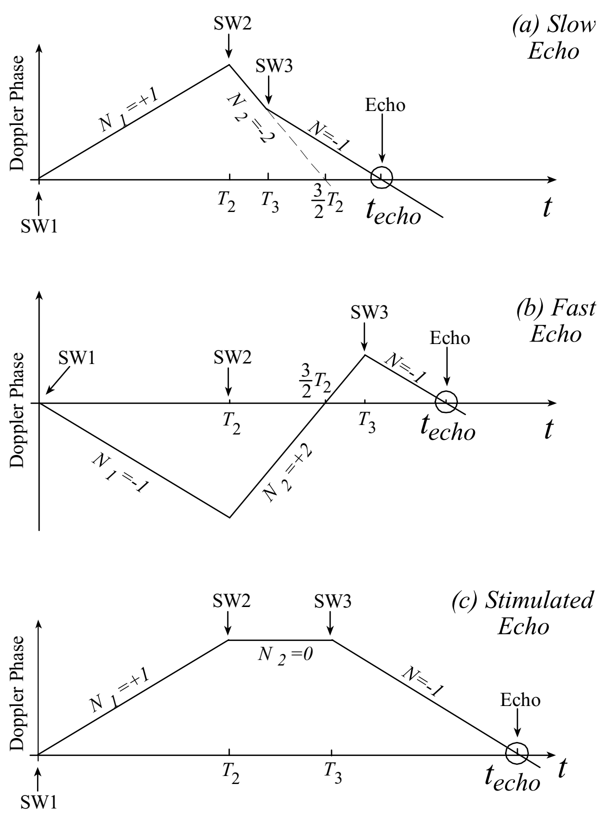


FIG. 13. Doppler phase diagrams for (a) Slow echo; (b) Fast echo; and (c) Stimulated echo.

Figure 14 shows typical echo signals from our experiments, obtained from the back scattering of a traveling wave from the sample as a function of time [as indicated in Fig. 11(b)].

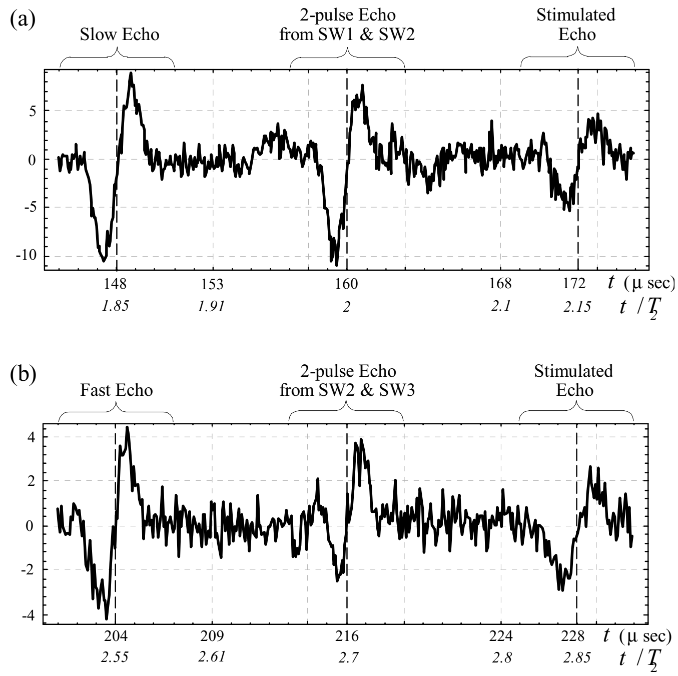


FIG. 14. Train of echoes, backscattered echo signal vs time: a) $T_2 = 80$ $\mu$sec and $T_3 = 92$ $\mu$sec. On this trace, the Slow echo, the two-pulse echo from SW1 and SW2, and the Stimulated echo are displayed. While the echoes in extreme left and right need all three standing-wave pulses for being generated, the echo in the middle needs only SW1 and SW2. b) $T_2 = 80$ $\mu$sec and $T_3 = 148$ $\mu$sec. This trace displays the Fast echo, the two-pulse echo from SW2 and SW3, and the Stimulated echo. The echo in the middle needs only SW2 and SW3 for being generated. Recoil diagram, explaining formation of the Slow, Fast, and Stimulated echo are presented in Fig. 13

### *3. Optical mask*

A more direct method than that described above for measuring atomic density distributions of period $\lambda/2$ (or fractions thereof) is by use of an *optical mask*. We have initiated experiments to test an optical mask scheme for both production and detection of periodic atomic density distributions. In these preliminary experiments, two standing wave pulses were applied to the cold atoms. The frequency of these pulses was made resonant with the F = 3 to F$'$ = 3 transition ($5S_{1/2}$ to $5P_{3/2}$). The excited F$'$ = 3 hyperfine state can decay to the F = 2 ground hyperfine state (as well as the F = 3 ground state) allowing a net loss of atoms from the initial F = 3 ground state hyperfine level. The first pulse can be thought of as producing an atomic periodic structure, in that all atoms *not* at the nodes of the standing wave will be pumped into the F=2 hyperfine level, and effectively lost. If the nodes of the second pulse are scanned over one period of the standing wave, the fluorescence signal can be used as a measure of the distribution of the atoms remaining in the F=3 state after the first pulse. This is because all atoms *except* those at the nodes contribute to the signal.

In our experiments, the fluorescence signal from the trapped atoms was recorded during the second pulse for various positions of the nodes of the second standing wave. The results are show in the Figure 15. The larger signal at 180° indicates that we have created and detected an atomic density variation with a period of half an optical wavelength. Work is currently underway to improve the resolution of the technique.

### *4. Production of a bright atomic source*

An atomic beam apparatus was constructed using a recirculating oven as a source of Rb atoms. The properties of the beam were characterized from measurements of the absorption from a weak frequency scanned laser beam. Typical parameters are a beam velocity of about 500 m/s, with a longitudinal spread of about 40% (full width at half max). Typical densities were about $10^8$ atoms/cm$^3$ at 1 meter from the source, and atomic fluxes of about $5 \times 10^{12}$ atoms/second.

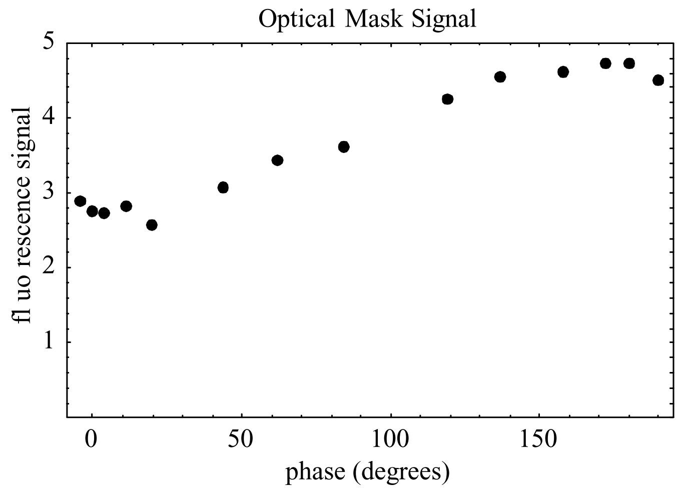


FIG. 15. Results of optical mask experiment. Fluorescence signal as a function of the shift in the nodes of the second standing wave relative to the first. A phase of zero corresponds to no shift in the position of the node, and a phase of 180° corresponds to a shift in the node by half the standing wave period.

### *5. Creation of magnetic coherence gratings in the atomic beam: magnetic grating free induction decay (MGFID)*

We have successfully obtained a *magnetic grating free induction decay signal* (MGFID), with a small angle between the two excitation laser beams (see Figure 16).

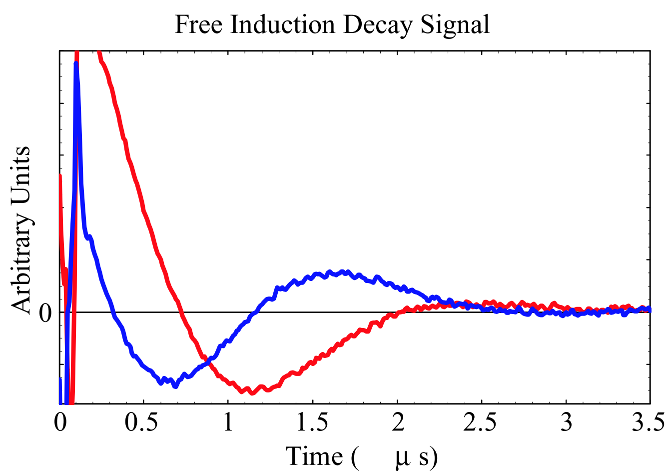


FIG. 16. Magnetic grating free-induction decay (MGFID) in an atomic beam. The red and blue curves show the two quadrature phases of the scattered signal.

This signal represents a spatially periodic atomic ground state coherence, which decays, due to the transverse velocity spread of the atoms. As in the case of laser-cooled atoms, the time dependence of the decay can be used to measure the transverse velocity distribution.

Attempts to obtain a MGFID signal with counter-propagating laser beams, as well as a *magnetic grating echo* signal were not yet successful. We are currently investigating the reason for this.

### *6. One dimensional transverse cooling of the atomic beam*

Experiments have been carried out on one dimensional transverse cooling of the atomic beam. The degree of cooling was determined by time-of-flight measurements of the velocity distribution. These measurements were made by imaging the fluorescence from the atomic beam downstream from the cooling region to get the size of the beam. The results of these experiments indicate that significant cooling is taking place. Although a smaller transverse velocity spread should result in a MGFID signal of longer duration, no such effect was observed. We are currently trying to understand the relationship between the time-of-flight cooling results, and the lack of the effect of cooling on the MGFID signal.

Resolution of these problems will allow us to proceed to the next step of producing atomic density gratings in the atomic beam by the application of optical standing waves.

## IV. PUBLICATIONS

### A. Papers published in peer reviewed journals


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5. A. Kumarakrishnan, S. Cahn, U. Shim, T. Sleator, "Magnetic Grating Echos from Laser Cooled Atoms", Physical Review A, **58**, R3387 (1998).

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**B. Papers published in non-peer-reviewed journals or conference proceedings**

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**C. Papers presented at meetings but not published in conference proceedings**

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10. Andrey Turlapov, D. V. Strekalov, A. Kumarakrishnan, S. B. Cahn, and Tycho Sleator, "Periodic atomic structures fabricated in a time-domain interferometer," Int. Conf. Atom Optics Applications, 23 - 28 May 1999, Les Houches, France.
11. Andrey Turlapov, D. V. Strekalov, A. Kumarakrishnan, S. B. Cahn, and Tycho Sleator, "Sub-optical wavelength atomic gratings generated in a time-domain interferometer," Centennial Meeting of the American Physical Society, March 20-26, 1999, Atlanta, Georgia.

12. Dmitry Strekalov, Andrey Turlapov, A. Kumarakrishnan, Sidney Cahn, and Tycho Sleator, "Phase Space Imaging of Trapped Atoms Using Magnetic Sublevels Coherence," Centennial Meeting of the American Physical Society, March 20-26, 1999, Atlanta, Georgia.

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## V. PARTICIPATING SCIENTIFIC PERSONNEL

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Andreas Karpf: Graduate student
Zayd Khaliq: Undergraduate student
Conan Chadbourn: Undergraduate student
Richard Martelly: Undergraduate student
Matt Know: Undergraduate student
William Kuhlman: Undergraduate student
Andy Vidan: Undergraduate student

## VI. REPORT OF INVENTIONS

None. A patent application was submitted to the University of Michigan for the conical lens, but the University decided not to pursue this application.

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